GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. _____

Project No. E-16-696 DATE 1/28/82

Project Director: Warren C. Strahle School/Lab Aerospace Engineering

Sponsor: National Science Foundation; Washington, D. C.

Type Agreement: Amendment No. 1 to Grant MEA-8022366/84

Award Period: From 2/1/82 To ~~8/31/83~~ 7/31/84 (Performance) _____ (Reports)

Sponsor Amount: $68,012 (second year funding only) Contracted through:

Cost Sharing: $3,401 (second year funding only) GTRI/~~GIT~~

Title: Pressure Velocity Correlation in Reacting Turbulent Flows

ADMINISTRATIVE DATA OCA Contact Leamon R. Scott

1) Sponsor Technical Contact:

George K. Lea
National Science Foundation
Fluid Mechanics Program
Mechanical & Engineering Group
Civil & Mechanical Engineering
Washington, D. C. 20550
202-357-9542

2) Sponsor Admin/Contractual Matters:

Al Rice
National Science Foundation
Division of Grants & Contracts
Section 1 AAEO/ENG Branch
Washington, D. C. 20550
202-357-0626

Defense Priority Rating: N/A Security Classification: N/A

RESTRICTIONS

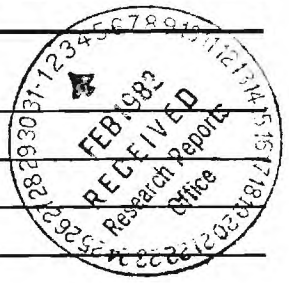
See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

COMMENTS:

Continuation of E-16-602



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Other _____

FORM OCA 4:781

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 8/9/85

Project No. E-16-696 School/~~Lab~~ AE

Includes Subproject No.(s)

Project Director(s) Warren C. Strahle GTRC / ~~GIT~~

Sponsor National Science Foundation

Title Pressure Velocity Correlation in Reacting Turbulent Flows

Effective Completion Date: 7/31/84 (Performance) 7/31/84 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [ ] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [X] ~~Final Report of Inventions~~ Patent Questionnaire
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. E-16-602 Continued by Project No.

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FORM OCA 69.285

E-16-696

PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION
Cover Page

FOR CONSIDERATION BY NSF ORGANIZATIONAL UNIT (Indicate the most specific unit known, i.e. program, division, etc.)	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? Yes ___ No X ; IF YES, LIST ACRONYM(S):
Fluid Mechanics Program Mechanical Science & Engineering Group Civil & Mechanical Engineering	

PROGRAM ANNOUNCEMENT/SOLICITATION NO.:	CLOSING DATE (IF ANY):
None	None

NAME OF SUBMITTING ORGANIZATION TO WHICH AWARD SHOULD BE MADE (INCLUDE BRANCH/CAMPUS/OTHER COMPONENTS)

Georgia Tech Research Institute

ADDRESS OF ORGANIZATION (INCLUDE ZIP CODE)

Administration Building
Georgia Institute of Technology Atlanta, GA 30332

TITLE OF PROPOSED PROJECT

Pressure Velocity Correlation in Reacting Turbulent Flows

REQUESTED AMOUNT	PROPOSED DURATION	DESIRED STARTING DATE
$ 75,858	1 yr.	1 February 1983

PI/PD DEPARTMENT	PI/PD ORGANIZATION	PI/PD PHONE NO.
School of Aerospace Engineering	Georgia Institute of Technology	(404) 894-3032

PI/PD NAME	SOCIAL SECURITY NO.*	DATE OF HIGHEST DEGREE ACHIEVED	MALE*	FEMALE*
Warren C. Strahle	558 48 0808	2/64	X	
ADDITIONAL PI/PD				
ADDITIONAL PI/PD				
ADDITIONAL PI/PD				
ADDITIONAL PI/PD				

FOR RENEWAL OR CONTINUING AWARD REQUEST, LIST PREVIOUS AWARD NO.:	IF SUBMITTING ORGANIZATION IS A SMALL BUSINESS CONCERN, CHECK HERE ☐ (See CFR Title 13, Part 121 for Definitions)
MEA -8022366	

* Submission of SSN and other personal data is voluntary and will not affect the organization's eligibility for an award. However, they are an integral part of the NSF information system and assist in processing proposals. SSN solicited under NSF Act of 1950, as amended.

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW:

☐ Animal Welfare	☐ Human Subjects	☐ National Environmental Policy Act
☐ Endangered Species	☐ Marine Mammal Protection	☐ Research Involving Recombinant DNA Molecules
☐ Historical Sites	☐ Pollution Control	☐ Proprietary and Privileged Information

PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR	AUTHORIZED ORGANIZATIONAL REP.	OTHER ENDORSEMENT (optional)
NAME Warren C. Strahle	NAME G. D. Hutchison	NAME
SIGNATURE	SIGNATURE	SIGNATURE
TITLE Regents' Professor	TITLE Contracting Officer Contract Administration	TITLE
DATE 10/15/82	DATE 10/18/82	DATE

NOTICE OF RESEARCH PROJECT
SCIENCE INFORMATION EXCHANGE
SMITHSONIAN INSTITUTION
NATIONAL SCIENCE FOUNDATION
PROJECT SUMMARY

PROJECT NO. (Do not use this space)
NSF AWARD NO.

1. NAME OF INSTITUTION (INCLUDE BRANCH/CAMPUS & SCHOOL OR DIVISION)

School of Aerospace Engineering

2. MAILING ADDRESS

Georgia Institute of Technology
Atlanta, Georgia 30332

3. PRINCIPAL INVESTIGATOR AND FIELD OF SCIENCE/SPECIALTY

Warren C. Strahle Turbulent Reacting Flows

4. TITLE OF PROJECT

Pressure Velocity Correlation in Reacting Turbulent Flows

5. SUMMARY OF PROPOSED WORK (LIMIT TO 22 PICA OR 18 ELITE TYPEWRITTEN LINES)

Technical abstract

Continuation funding is proposed for theoretical and experimental investigation of the problem of correlation between velocity fluctuations and pressure gradient in reacting turbulent flows. Work in the past year and three quarters has produced measurements, theory and theoretical-experimental comparisons which show the great importance of the subject correlation in turbulent stress production. Current work is moving toward non-intrusive LDV and laser Rayleigh scattering techniques to remove objections to intrusive diagnostics.

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DIVISION (OFFICE) AND DIRECTORATE	PROGRAM	
SECTION	PROPOSAL NO.	F.Y.

FOR DGC USE ONLY

START AND END DATES	AMOUNT GRANTED

FORM 4 (7-78) 1. Proposal Folder 2. Program Suspense 3. Division of Grants & Contracts 4. Science Information Exchange 5. Principal Investigator 6. Off. of Govt. & Pub. Progs. 7. Assistant Director

REQUEST

This proposal is to request the third increment of funding for program CME-8022366, "Pressure Velocity Correlation in Reacting Turbulent Flows". Substantial progress has been made in the past year on both the analytical and experimental fronts, and the work has been widely recognized. The dollar amount requested is in line with prior estimates.

PROGRESS REPORT

The program, as of this writing, has been underway for 21 months. Significant progress in theoretical and experimental work is as follows:

1. The first known measurement of the $\overline{p' v'}$ correlation in a reactive turbulent flow has been accomplished by intrusive measurements on a premixed jet flame. Simultaneous stagnation pressure, temperature, and heat transfer (velocity) measurements were performed in a small measurement volume at various stations along the flame axis.

2. The correlation is large and produces a contribution as mechanical work in the turbulent stress equations which cannot be ignored.

3. After several initial developments for simple flames, a fully three dimensional model for the $\overline{v_k'' \frac{\partial p}{\partial x_i}}$ correlation has been developed. It has been checked in the constant density limit for some classical flows and been found reasonable. It has been applied to a turbulent jet diffusion flame and found to bring excellent agreement between theory and experiment.

4. The theoretical model predicts an intense source of turbulence in premixed, one-dimensional flames, in accordance with experimental expectations.

The three dimensional model for $\overline{v_k'' \partial p/\partial x_i}$, which is the correlation which directly appears in turbulence stress equations, represents a marked departure from past practice. This model is currently under peer review, but is bound to stir up some controversy. Its success, however, in the diffusion flame and premixed flame problems attest to its usefulness. Direct measurement of this quantity has proved elusive, however, because a gradient is involved. The derivative taxes intrusive measurement methods. In order to counter this limitation a new experimental rig has been constructed and is currently under checkout. In this rig, LDV will be employed for velocity measurements, and it is hoped that laser Rayleigh scattering may be used for density determination. The pressure measurement, as always, will have to be made intrusively.

The following publications and presentations have resulted from this grant:

Refereed Publications

1. Strahle, W. C. and Chandran, S. B. S., "Pressure-Velocity Correlation in a Reactive Turbulent Flow," AIAA J 20, 129-135 (1982).

2. Strahle, W. C., "Estimation of Some Correlations in Reactive Turbulent Flows," Combustion Science and Technology (in press).

3. Strahle, W. C., "Duality, Dilatation, Diffusion and Dissipation in Reactive Turbulent Flows," 19th Symposium (International) on Combustion (in press).

4. Chandran, S. B. S. and Strahle, W. C., "The Effect of Pressure-Velocity Correlation in a Premixed, Planar, Turbulent Flame," Combustion and Flame (in review).

5. Strahle, W. C., "Velocity-Pressure Gradient Correlation in Turbulent Reactive Flows," Journal of Fluid Mechanics (in review).

Other Publications

1. Strahle, W. C., "Pressure Velocity Correlation in a Reactive Turbulent Flow," AIAA Paper No. 81-0108 (1981).

2. Komerath, N. M. and Strahle, W. C., "Measurement of the Pressure-Velocity Correlation in Turbulent Reactive Flows," AIAA Paper No. 83-0400 (to be printed in January, 1983).

Verbal presentations have been made of papers 1 and 3 under Refereed Publications above, where # 3 was an invited paper at the 19th Combustion Symposium in Haifa, Israel. Paper 2 under Other Publications will be presented at the 21st Aerospace Sciences Meeting. The senior author received his Ph.D under this program.

EE INSTRUCTIONS ON
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Third Year
SUMMARY
PROPOSAL BUDGET

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)RGANIZATION School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, Ga. 30332

PROPOSAL NO. | DURATION (MONTHS) Proposed | Granted

'RINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Dr. Warren C. Strahle

AWARD NO.

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	NSF FUNDED PERSON-MOS. CAL.	ACAD	SUMR	FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
Dr. Warren C. Strahle	3			$ 19,259	$
( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
(1) TOTAL SENIOR PERSONNEL (1-5)	3			19,259	
OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
(1) POST DOCTORAL ASSOCIATES	6			9,000	
(1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	1			2,923	
(1) GRADUATE STUDENTS 1/3 time				7,400	
( ) UNDERGRADUATE STUDENTS					
(1) SECRETARIAL-CLERICAL 1/12 time				1,197	
(2) OTHER Technical Shop 1/24 time each				2,900	
TOTAL SALARIES AND WAGES (A+B)				42,679	
FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) @ 21% of A6, B2, B5, & B6; 9% of B1				6,329	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				49,008	
C. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000; ITEMS OVER $10,000 REQUIRE CERTIFICATION)					
TOTAL PERMANENT EQUIPMENT					
D. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				750	
2. FOREIGN					
E. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $					
2. TRAVEL					
3. SUBSISTENCE					
4. OTHER					
TOTAL PARTICIPANT COSTS					
F. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES Propane, Elec., Supplies, Mag.Tape, Instrument Rep.				926	
2. PUBLICATION COSTS/PAGE CHARGES 10 pp @ $85/page				850	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES Departmental computers used				0	
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				1,776	
TOTAL DIRECT COSTS (A THROUGH G)				51,534	
INDIRECT COSTS (SPECIFY) 47.2% of H					
TOTAL INDIRECT COSTS				24,324	
TOTAL DIRECT AND INDIRECT COSTS (H + I)				75,858	
RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS GPM 252 AND 253)					
AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 75,858	$

PD TYPED NAME & SIGNATURE*
Warren C. Strahle

DATE 10/15/82

ST. REP. TYPED NAME & SIGNATURE
G. D. Hutchison

DATE 10/18/82

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INDIRECT COST RATE VERIFICATION
Date Checked | Date of Rate Sheet | Initials - DGC Program

SUPERSEDES ALL PREVIOUS EDITIONS

Current and Pending Support

Dr. Warren C. Strahle

		Supporting Agency	Project Title	Annual Rate	Period Covered	% of Effort Committed ACAD	% of Effort Committed SUMM	Location where Research Performed
A.	Current Support	NSF	Pressure Velocity Correlation in Reacting Turbulen Flows	$ 68,012	2/82-1/83	25%	25%	Georgia Tech
		AOR	Acoustic Signature from Flames as a Combustion Diagnostic Tool	$ 49,594	6/82-5/83	15%	15%	Georgia Tech
		AFOSR	Rocket Research at Georgia Tech	$285,000	10/82-9/83	25%	25%	Georgia Tech
B.	Proposals Pending	NSF	Renewal Proposal		2/83-1/84	25%	25%	Georgia Tech

E-16-696

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I–PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
School of Aerospace Engineering Georgia Institute of Technology Atlanta, Georgia 30332	Fluid Mechanics	MEA 8022366
	4. Award Period From 2/1/81 To 7/31/84	5. Cumulative Award Amount $ 211,114

6. Project Title

Pressure-Velocity Correlation in Reactive Turbulent Flows

PART II–SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

A combined experimental-analytical program was conducted to investigate the importance of correlation between velocity and pressure fluctuations in turbulent reactive flows. Models were constructed for the pressure-velocity correlation, valid in flows with high mean strain rate and away from walls, and they showed a clear source of turbulence in premixed flames. When applied to data for an H_2 - air diffusion flame, interesting features were explained which were not previously explainable. Two experimental configurations using propane-air premixed turbulent flames were used. Simultaneous sensing of temperature, static pressure and velocity was required and was accomplished with various combinations of heat flux, pitot and thermocouple probes along with laser velocimetry and Rayleigh molecular scattering. The fundamental conclusion was that correlation between pressure and velocity plays an important role in both premixed and non-premixed reacting turbulent flows. A necessary next step is the measurement of the correlation between velocity and pressure gradient, requiring a two-point measurement.

PART III–TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (✓)	Approx. Date
a. Abstracts of Theses		X			
b. Publication Citations		X			
c. Data on Scientific Collaborators		X			
d. Information on Inventions	X				
e. Technical Description of Project and Results		X			
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
Warren C. Strahle		

Form Approved OMB No. 99R0013

Dissertation abstracts generated in this program

Measurement of Pressure-Velocity Correlations in Turbulent Reacting Flows

Narayanan M. Komerath

August, 1982

The pressure-velocity correlation has long posed a major obstacle to the modeling of turbulent flows, due to difficulties in measuring fluctuating pressure and velocity simultaneously in a flow-field. Measurements in hot reacting flows encountered in propulsion devices require a new approach.

Static pressure fluctuations and the pressure-velocity correlation are derived from simultaneous measurements of total pressure, heat transfer and temperature. A microphone Pitot probe has been developed and tested for this application. Hot-film and cooled-film anemometer probes have been used to measure heat transfer. Coated platinum-rhodium fine-wire thermocouples have been used to measure temperature.

Voltage signals from the probes, recorded simultaneously, are analyzed using a Fourier Analyzer System. The probe systems are treated as constant-parameter linear systems, and statistical time series analysis is employed to get power- and cross-spectra and the required correlations. Methods for digital frequency-response compensation of the signals are described.

The response of the microphone probe is determined by dynamic calibration, while that of the thermocouples is derived from cross-spectral analysis of the raw data. Cooled-film response is computed from an

analytical model. Velocity spectra are extracted from cooled-film spectra by cross-spectral analysis with a thermocouple signal.

The simpler case of fully developed cold turbulent pipe flow was first studied. Reacting flow studies were then conducted using a premixed turbulent propane-air jet flame. Results obtained in both flows show that the pressure fluctuation is broad-band, and is of the order of the product of density, velocity, and r.m.s. velocity fluctuation. The pressure-velocity correlation is negative and the correlation coefficient is near unity. The correlation is of the same order as other terms in the turbulent kinetic energy equation.

Analysis of Pressure Gradient-Correlation in

Reactive Turbulent Flows

Subhash B. S. Chandran

May, 1984

The correlation of pressure and velocity as it occurs in the turbulent stress equations is often neglected in the analysis of turbulent reacting flows. This is mainly because of the difficulties in modelling these correlations and the problems in determining these correlations experimentally. Modelling of the pressure-velocity correlations is made difficult due to the heat release and the ensuing dilatation. These same problems contribute to the difficulties in measuring pressure in reacting flows. An analytical study of planar premixed flames using models for the

pressure correlations and an experimental determination of these correlations in a premixed flame are done here.

The models are developed by expressing pressure in terms of the velocity field. This is done by obtaining a Poisson equation for a variable which depends on pressure and by solving the equation. Using this solution, the pressure-velocity correlation can be expressed in terms of velocity correlations. This model is used in the prediction of the flow field in a planar, turbulent, premixed flame. Both gradient and nongradient models are used in closing the governing equations. In both cases the pressure gradient-velocity correlation is a source of turbulent kinetic energy and for values of the parameter, which controls the size of the model, of order unity the correlation overcomes the dilatation term and increases the turbulent kinetic energy through the flame.

The experimental determination of the pressure-velocity correlation is carried out in an axysymmetric, premixed flame. Pressure is measured using a cooled pitot probe. A microphone sensor in the probe convertsthe total pressure fluctuations to voltage fluctuations. Since the total pressure fluctuations are dependent on velocity and temperature, they have to be obtained simultaneously with the pressure probe signals. Velocity is measured by a laser Doppler velocimeter and temperature by thermocouples. The pressure probe is calibrated for its response at different temperatures. All the signals are sampled and spectra are obtained by fast Fourier transform techniques. The correlation coefficient is obtained by the inverse transform of these spectra.

The mean and rms velocities demonstrate local maxima in the flame zone. Near the flame, the turbulent flux of energy and momentum show existance of countergradient diffusion. The pressure gradient velocity correlations obtained from measurement are of the same order as the other source terms in the equations for turbulent stress.

Publication Citations

1. W. C. Strahle and S. B. S. Chandran (1982) "Pressure-Velocity Correlation in a Reactive Turbulent Flow," AIAA J. 20, 129.

2. W. C. Strahle (1982) "Estimation of Some Correlations in a Reactive Turbulent Flow," Combustion Science and Technology, 29, 243.

3. S. B. S. Chandran and W. C. Strahle (1983) "The Effect of Pressure-Velocity Correlation in a Premixed, Planar, Turbulent Flame," Combustion and Flame, 51, 313.

4. W. C. Strahle (1983) "Duality, Dilatation, Diffusion and Dissipation in Reacting Turbulent Flows," Nineteenth Symposium (International) on Combustion, The Combustion Institute, 337.

5. W. C. Strahle (1983) "Velocity-Pressure Gradient Correlation in Reactive Turbulent Flows," Combustion Science and Technology, 32, 289.

6. N. M. Komerath and W. C. Strahle (in review) AIAA Journal.

7. S. B. S. Chandran, N. M. Komerath and W. C. Strahle (accepted, 1984) "Scalar-Velocity Correlation in a Turbulent Premixed Flame," Twentieth Symposium (International) on Combustion.

8. S. B. S. Chandran, N. M. Komerath, W. M. Grissom, J. I. Jagoda and W. C. Strahle (in review), "Time Resolved Thermometry by Simultaneous Thermocouple and Rayleigh Scattering Measurements in a Turbulent Flame," Combustion Science and Technology.

Data on Scientific Collaborators

Dr. Narayanan Komerath - Graduate Research Assistant, Post-doctoral Fellow and Research Engineer.

Dr. Subhash B. S. Chandran - Graduate Research Assistant.

Mr. Ronald E. Walterick - Research Engineer

Technical Summary

A combined experimental-analytical program was conducted to investigate the importance of correlation between velocity and pressure fluctuations in turbulent reactive flows. Models were constructed for the pressure-velocity correlation, valid in flows with high mean strain rate and away from walls, and they showed a clear source of turbulence in premixed flames. When applied to data for an H_2 - air diffusion flame, interesting features were explained which were not previously explainable. Two experimental configurations using propane-air premixed turbulent flames were used. Simultaneous sensing of temperature, static pressure and velocity was required and was accomplished with various combinations of heat flux, pitot and thermocouple probes along with laser velocimetry and Rayleigh molecular scattering. The fundamental conclusion was that correlation between pressure and velocity plays an important role in both premixed and non-premixed reacting turbulent flows. A necessary next step is the measurement of the correlation between velocity and pressure gradient, requiring a two-point measurement.